TRACKING COASTAL CHANGE IN AMERICAN SAMOA BY MAPPING LOCAL VERTICAL LAND MOTION WITH PS-INSAR

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ABSTRACT

Characterizing diverse contributions to coastal land change is a key step to mitigating the effects of rising sea levels that threaten coastal communities. This task is particularly critical for small island communities in tectonically active regions, which are highly vulnerable to the effects of sea level rise. We highlight here a case study to extract regional estimates of vertical land motion (VLM) over American Samoa, which in recent years has observed increased nuisance flooding. We used persistent scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) to derive high-resolution estimates of crustal deformation in populated regions over Tutuila Island from 2016 to 2021. While the area is small and highly vegetated and poses challenges for InSAR, we were able to construct a regional map of the estimated deformation rate in these areas and validate the time-series with a local GPS station. Our preliminary results suggest that PS-InSAR has the ability to capture local and regional deformation patterns. Further work to refine our VLM estimate will include models to account for more complex atmospheric effects and estimates of error margins, as well as integration of our results into models of sea-level change that can be used by local stakeholders.

***Index Terms*—** sea-level rise, coastal change, vertical land motion (VLM), interferometric synthetic aperture radar (InSAR), persistent scatterers

1. INTRODUCTION

Sea-level change presents increasing challenges to coastal communities. Rising waters can increase the incidence of minor and major flooding that threatens existing residences and cause damage to local infrastructure and other key resources. Such effects are particularly severe for island communities and states that have a large number of assets concentrated in coastal areas [1]–[3]. These problems can be further exacerbated in tectonically active regions since tectonic motion can lead to additional subsidence that further increases the relative sea level observed locally [4]. Accurately characterizing various local and global contributions to sea level rise in different regions is thus key to predicting future patterns of vertical land motion and developing effective policies to minimize the damaging effects of rising waters.

We focus here on American Samoa, an unincorporated US territory that is part of a volcanic archipelago in the western Pacific, as a case study for characterizing local differences in vertical land motion. Tutuila Island, the largest and most populated island in American Samoa, underwent an increase in the rate of land subsidence due to post-seismic deformation following the Samoa-Tonga earthquake in 2009; it is predicted that nuisance flooding will occur regularly starting from the current decade [5]. However, there remains uncertainty about the Earth rheological properties that govern the timing and pattern of future subsidence in this region and the contribution of local as opposed to larger scale processes that govern the observed subsidence.

We study here the use of Interferometric Synthetic Aperture Radar (InSAR) for measuring local- vs. broad-scale VLM over Tutuila Island, which serves as one key input for constraining alternative models of crustal deformation. InSAR is a remote sensing technique with high spatial resolution and moderate temporal resolution that spans several days to weeks in modern systems, depending on the constellation design. Advanced time-series InSAR techniques applied to high-quality data have measured crustal deformation down to accuracies of mm/yr in the line-of-sight (LOS) direction [6]–[8], which in practice is primarily vertical motion for spaceborne systems. However, even advanced InSAR time-series techniques can return less meaningful results over highly vegetated regions and isolated landmasses due to the larger unwrapping

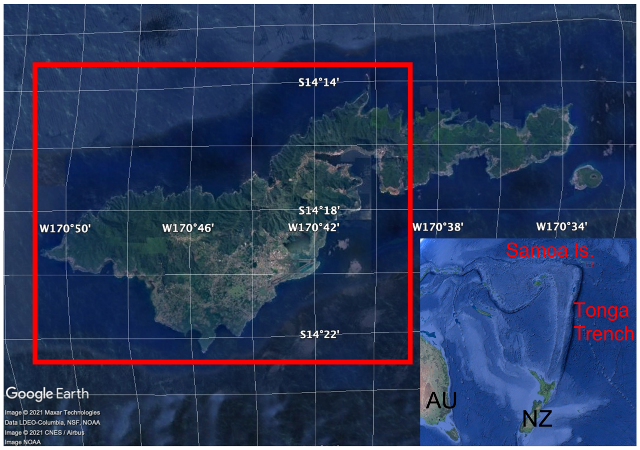

Fig. 1. Approximate study area outlined in red. Optical satellite imagery obtained through Google Earth. The inset shows the approximate location of the red square in the Pacific Ocean.

artifacts, complex atmospheric noise, and decorrelation noise introduced by this tropical region. As such, this has made applying InSAR more challenging over islands such as Tutuila. Here, we make a first pass at applying InSAR over the island and use the persistent scatterer InSAR (PS-InSAR) technique to focus our measurements to the more populated regions of Tutuila Island, which are highly correlated and thus more amenable to InSAR analysis compared to the more highly vegetated regions of the island.

2. DATA AND METHODOLOGY

We processed Sentinel-1A data over Tutuila Island in American Samoa. Our study region is shown in Fig. 1 and covers most of the island; the inset shows the relative location of American Samoa in the Pacific Ocean. For this study, we have excluded the eastern side of the island to avoid an abrupt transition between subswaths in the satellite acquisition that cuts through the land mass. There is also a much lower density of coherent and phase-stable points on the eastern side of the island. We use all available data from November 3, 2016, to December 31, 2021 (path 51, frame 1133), acquired in ascending tracks in Interferometric Wide (IW) mode, which has a slant range resolution of 5 m and azimuth resolution of 20 m. The data are acquired at C-band (wavelength = 5.55 cm) with HH polarization. All data are publicly available through the European Space Agency (ESA) and can be accessed from the open archive managed by the Alaska Satellite Facility Distributed Active Archive Center (ASF DAAC).

Fig. 2. Locations of the high-correlation pixels used as reference points in our study, overlaid on optical satellite imagery from Google Earth. Also marked is the location of the GPS site used in this study, ASPA.

We formed single look complex (SLC) images from Level-0 (L0) data using backprojection, which directly coregisters all images to our chosen digital elevation model (DEM) during focusing. The data are not multilooked once they are coregistered to the DEM. We used the freely available NASADEM, which is reprocessed data from the Shuttle Radar Topography Mission (SRTM) and has a resolution of 30 m over our area in the WGS84 reference coordinate system. We chose the July 15, 2019 scene as the primary image. We applied the non-Gaussian maximum likelihood (NG MLE) PS detector described in [9]; this detector has been shown to operate well in mixed natural terrain. The detector requires an estimate of the parameter alpha, which describes the heterogeneity of the region, and can be obtained by fitting the backscatter amplitude of one scene to the G^0 distribution; we obtain an alpha parameter of 2.973. We choose as PS all points with a signal-to-clutter ratio (SCR) above 3.1; this value is an empirically chosen for this region to be the threshold at which there are no more points in the ocean that are identified as PS. The PS were applied as a mask to the interferogram stack, and then interpolated using the nearest neighbor algorithm as in [10] and unwrapped using the SNAPHU algorithm [11]. We then de-ramped each scene in the stack by fitting a plane to the phases across the image and subtracting the plane. Further, we corrected for the tropospheric phase contribution using the method of [12] by estimating a linear trend of phase with elevation across high-SCR points and removing the trend from the phase data. Finally, we referenced our measurements to the average signal from a set of five high-correlation points, shown in Fig. 2.

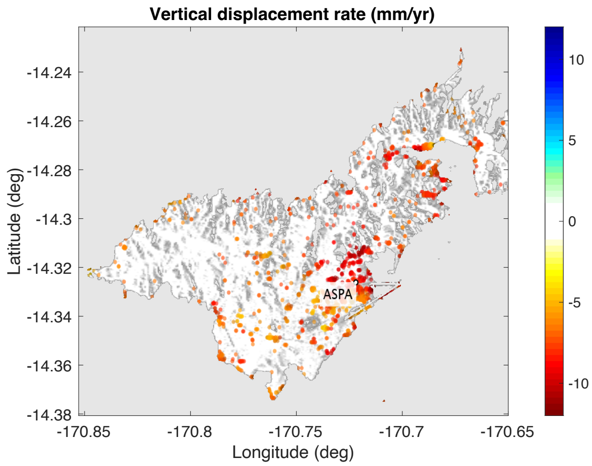

Fig. 3. Vertical deformation map of Tutila Island overlaid on a masked amplitude image, with the location of the GPS station marked. Average rate of deformation shown in mm/yr.

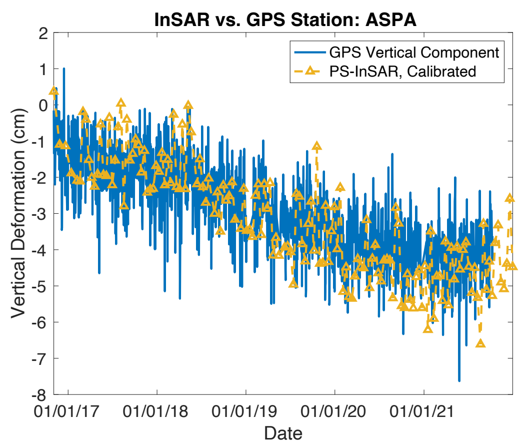

Fig. 4. Time-series of vertical deformation from November 3, 2016, to December 31, 2021, derived from PS-InSAR (dotted line with triangles) and compared with GPS (blue, solid line, data only available until October 9, 2021).

In order to tie the InSAR measurements to a global geodetic reference frame, we calibrated the estimated displacement with the vertical deformation rate observed using continuous GPS measurements. One permanent station is available on the island at ASPA (latitude = -14.326, longitude = -170.722; marked in Fig. 2). We used the fixed-plate solutions available from the University of Nevada Geodetic Laboratory, which provides estimates until October 9, 2021 [13]. The deformation rate was well-approximated with a linear trend, and we found the average rate of vertical deformation observed at the station over this time period was approximately -7 mm/yr.

As a form of validation, we compared the estimated deformation from PS-InSAR with the measurements from the ASPA station. We averaged the PS-InSAR phase measurements over the 20 closest PS points to the station before calibrating with the linear trend observed at ASPA, as described above.

4. RESULTS AND DISCUSSION

A map of estimated vertical deformation rates around the island is shown in Fig. 3, overlaid on a masked amplitude image of the observed backscatter. The measurements suggest that the region directly north of the ASPA station is subsiding the most quickly compared to the rest of the island, while the central and western portions of the island are subsiding the least. However, all observed points on the island appear to be subsiding at a rate of at least -5 mm/yr. While ASPA is the only long-term permanent GPS station on the island from which an independent deformation estimate is available, VLM can also be computed from a tide gauge station in Pago Pago Harbor and new GPS sites near the harbor have been installed. These habor area sites would offer an additional method to verify the spatial patterns of deformation observed using InSAR.

Vertical deformation over time measured from the ASPA station is plotted with the InSAR-derived time-series in Fig. 4. Visual inspection of the two time-series shows a general consistency between the measurements. Fitting a linear trend to the PS-InSAR time-series reveals a slightly higher rate of deformation, at around -8 mm/yr, compared to the GPS-derived rate of -7 mm/yr. We are continuing to investigate whether particular noise sources (e.g., tropospheric and ionospheric atmospheric effects) could contribute to this discrepancy, or whether it could result from measurable physical processes (e.g., a difference in surface/seasonal deformation vs. deformation at depth).

5. CONCLUSION

Our initial results show that we are able to derive an estimate of regional differences in land subsidence over Tutuila Island with PS-InSAR. Further work is needed to resolve discrepancies with the estimated deformation rate when compared to GPS data and better understand the ability of InSAR to accurately capture the regional differences around the island, including a comparison with tide gauge measurements in Pago Pago Harbor. Further work will also focus on incorporating existing tools for data correction that rely on advanced ionospheric correction schemes. Accurate InSAR measurements can thus be incorporated with other geodetic measurements to provide a better

understanding of local differences in VLM and shed light on expected patterns of future subsidence in the region, enabling local policymakers to make decisions about combatting the negative effects of rising sea levels.

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Copernicus Sentinel data 2015-2021 were provided by ASF DAAC, accessed 7 January 2021 from https://asf.alaska.edu.

7. REFERENCES

[1] J. Hinkel *et al.*, "Coastal flood damage and adaptation costs under 21st century sea-level rise," *Proc. Natl. Acad. Sci. U. S. A.*, vol. 111, no. 9, pp. 3292–3297, 2014, doi: 10.1073/pnas.1222469111.

[2] B. D. Hamlington *et al.*, "Understanding of Contemporary Regional Sea-Level Change and the Implications for the Future," *Rev. Geophys.*, vol. 58, no. 3, pp. 1–39, 2020, doi: 10.1029/2019RG000672.

[3] R. Martyr-Koller, A. Thomas, C. F. Schleussner, A. Nauels, and T. Lissner, "Loss and damage implications of sea-level rise on Small Island Developing States," *Curr. Opin. Environ. Sustain.*, vol. 50, pp. 245–259, 2021, doi: 10.1016/j.cosust.2021.05.001.

[4] G. Wöppelmann and M. Marcos, "Vertical land motion as a key to understanding sea level change and variability," *Reviews of Geophysics*, vol. 54, no. 1. pp. 64–92, Mar. 2016. doi: 10.1002/2015RG000502.

[5] S. C. Han, J. Sauber, F. Pollitz, and R. Ray, "Sea Level Rise in the Samoan Islands Escalated by Viscoelastic Relaxation After the 2009 Samoa-Tonga Earthquake," *J. Geophys. Res. Solid Earth*, vol. 124, no. 4, pp. 4142–4156, Apr. 2019, doi: 10.1029/2018JB017110.

[6] R. Bamler and P. Hartl, "Synthetic aperture radar interferometry," *Inverse Probl.*, vol. 14, no. 4, pp. R1–R54, Aug. 1998, doi: 10.1088/0266-5611/14/4/001.

[7] M. Simons and P. A. Rosen, "Interferometric Synthetic Aperture Radar Geodesy," *Treatise Geophys.*, vol. 3, pp. 391–446, 2007, doi: 10.1016/B978-044452748-6.00059-6.

[8] R. Bürgmann, P. A. Rosen, and E. J. Fielding, "Synthetic Aperture Radar Interferometry to Measure Earth's Surface Topography and Its Deformation," *Annu. Rev. Earth Planet. Sci.*, vol. 28, no. 1, pp. 169–209, May 2000, doi: 10.1146/annurev.earth.28.1.169.

[9] S. A. Huang, "Statistical Theory for the Detection of Persistent Scatterers in InSAR Imagery," Stanford University, 2021. [Online]. Available: https://purl.stanford.edu/mh468vh5576

[10] P. S. Agram, "Persistent Scatterer Interferometry in Natural Terrain," Stanford University, 2010. doi: 10.14358/PERS.76.9.1061.

[11] C. W. Chen and H. A. Zebker, "Phase unwrapping for large SAR interferograms: Statistical segmentation and generalized network models," *IEEE Trans. Geosci. Remote Sens.*, vol. 40, no. 8, pp. 1709–1719, 2002, doi: 10.1109/TGRS.2002.802453.

[12] H. Zebker, "Accuracy of a model-free algorithm for temporal insar tropospheric correction," *Remote Sens.*, vol. 13, no. 3, pp. 1–9, 2021, doi: 10.3390/rs13030409.

[13] G. Blewitt, W. Hammond, and C. Kreemer, "Harnessing the GPS Data Explosion for Interdisciplinary Science," *Eos (Washington. DC).*, vol. 99, no. 10.1029, Sep. 2018, doi: 10.1029/2018EO104623.